Avoid common problems when designing op-amp and in-amp circuits

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Introduction

Modern operational amplifiers (op amps) and instrumentation amplifiers (in amps) provide great benefits to the designer, when compared with discrete semiconductors. But all too often, some very basic issue is overlooked which leads to a non-functional circuit. This article will discuss some of the most common applications problems and provide practical solutions.

1) Failure to provide a DC bias-current return path when using AC coupling

One of the most common applications problems encountered is the failure to provide a DC return path, or more specifically, a bias-current return path when AC coupling either op amps or in amps. In **Figure 1**, a capacitor has been placed in series with the non-inverting (+) input of an op amp.

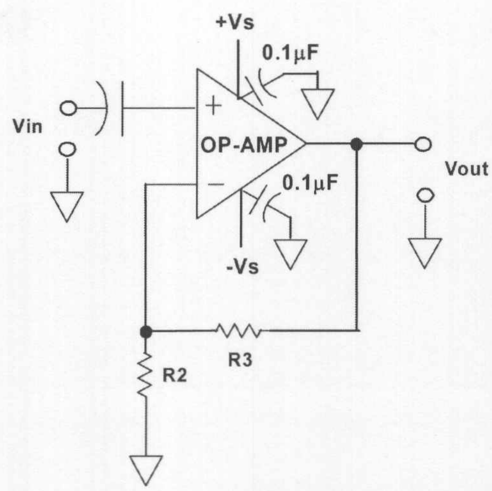

Figure 1: A non-functional, AC-coupled op amp circuit

AC coupling is an easy way to block dc voltages that are present at the in amp's inputs. This is especially useful in high-gain applications, where even a small DC voltage at an amplifier's input can limit its dynamic range. But AC coupling into a high impedance input, without providing a dc return, renders the circuit nonfunctional!

What actually happens is the input bias currents will charge up the AC coupling capacitors until the input common-mode voltage is exceeded. In other words, the caps will charge up to the positive supply

line, or down to the negative supply, depending on the direction of the input bias currents.

Of special concern is that it could take several minutes for the bias currents to charge up a FET-input device when using very large AC input-coupling capacitors, so there may be a long delay before the amplifier is rendered inoperative. As a result, a casual lab test might not detect this problem, leading to circuit failure in the field. Therefore, it's very important to avoid this problem altogether.

Figure 2shows a simple solution to this very common problem.

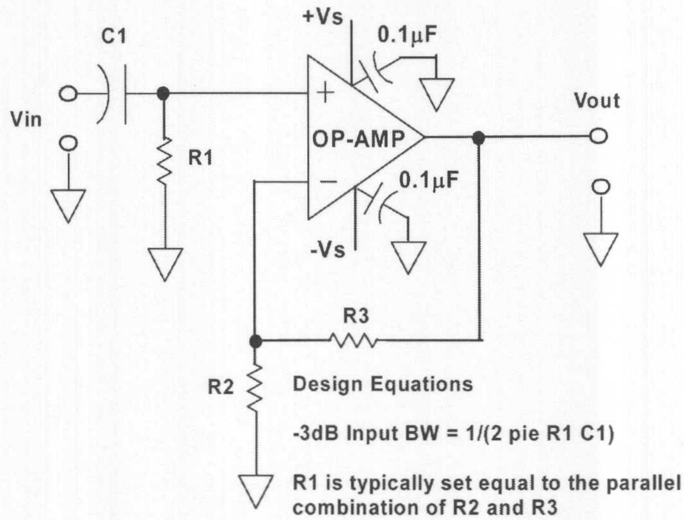

Figure 2: Correct method for AC coupling an op-amp input for dual-supply operation

In this circuit, a resistor is connected between the op-amp input and ground, to allow the input bias currents to flow. For lowest input-offset currents using bipolar op amps, R_1 is usually set equal to the parallel combination of R_2 and R_3.

Note, however, that this resistor will always introduce some noise into the circuit, so there will be a tradeoff between circuit input impedance, the size of the input-coupling capacitor needed, and the Johnson noise added by the resistor. Practical resistor values vary from around 100 kΩ to 1 MΩ.

A similar problem affects instrumentation amplifiers. **Figure 3a** and **Figure 3b** show in-amp circuits which are AC coupled using two capacitors but which, again, do not provide an input bias-current return path. This problem is common with both single and dual power-supply in-amp circuits.

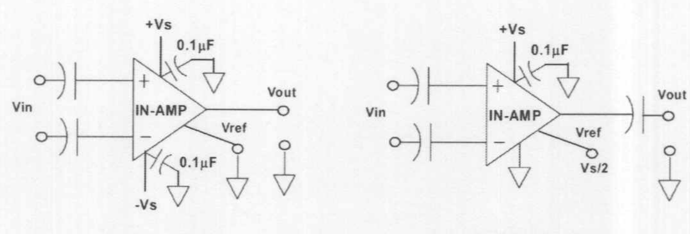

Figure 3: Examples of non-functional, AC-coupled in-amp circuits

Figure 4 shows a transformer-coupled circuit. This circuit is non-functional since it, too, does not

provide a DC return path to ground.

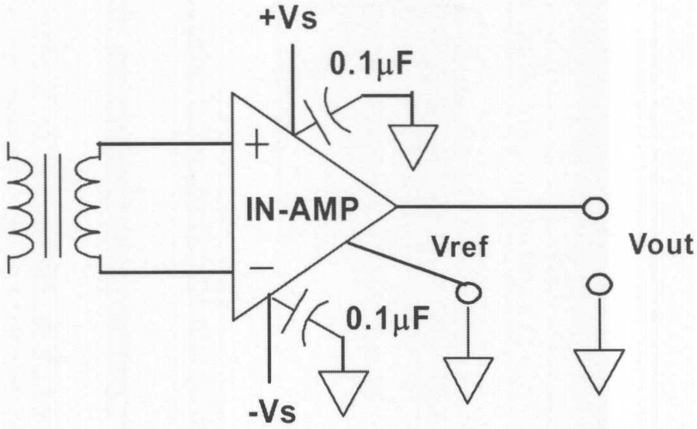

Figure 4: A non-functional, transformer-coupled, in-amp circuit

Simple solutions for these circuits are shown in **Figure 5** and **Figure 6**. Here, a high-value resistance (R_a, R_b) is added between each input and ground. This is a simple and practical solution for dual-supply in-amp circuits.

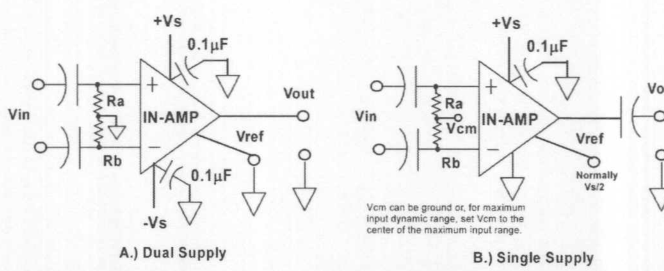

Figure 5: A high-value resistor between each input and ground supplies the necessary bias-current return path

The resistors allow a discharge path for input bias currents. In the dual-supply example of Figure 5a, both inputs are now referenced to ground. In the single-supply example of Figure 5b, the inputs may either be ground referenced (V_{cm} tied to ground) or connected to a bias voltage equal to the midpoint of the maximum input-voltage range.

Figure 6 shows a typical solution for transformer coupled inputs. In these circuits, there will be a small offset-voltage error due to the mismatch between the input bias currents flowing through the two non-identical resistors. To avoid errors due to an R_a/R_b mismatch, a third resistor, of about one-tenth their value, can be connected between the two in-amp inputs (thus bridging both resistors).

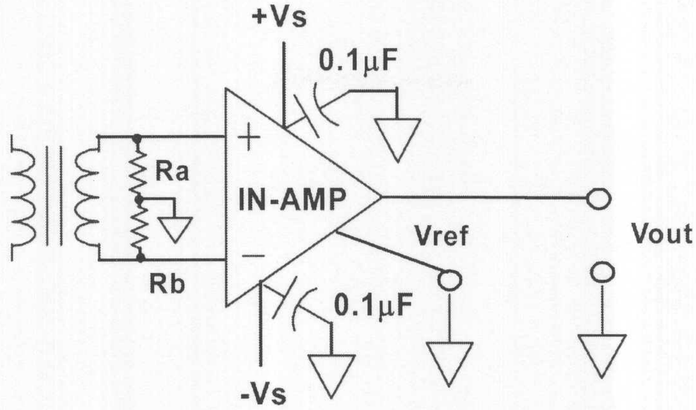

Figure 6: Correct method for transformer input coupling to an in amp

Note that, when using transformers with a center-tapped secondary winding, this can often be grounded directly, thus avoiding the need for the two resistors.

2) Supplying reference voltages for in amps, op amps, and ADCs
Figure 7 shows a single-supply circuit where an in amp is driving an analog/digital converter (ADC). Many such circuits use resistor dividers or other simple methods to supply the in amp and ADC reference voltages.

Note that the two reference voltages may be quite different. As shown, a simple RC low-pass filter is often used between in-amp output and ADC input to reduce noise.

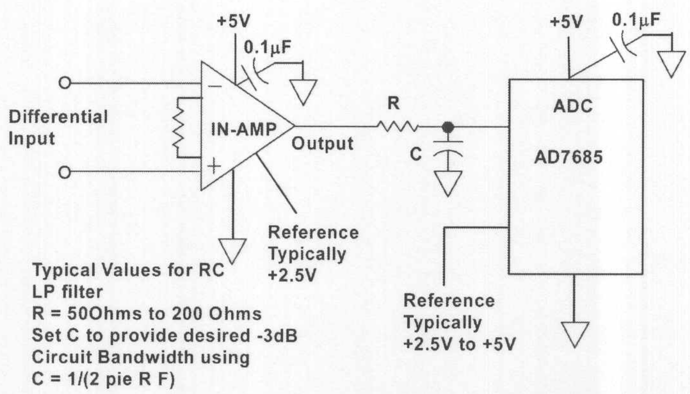

Figure 7: A typical single-supply circuit where an in-amp is driving an ADC
(Click on figure to enlarge)

3) Driving in-amp reference inputs
A common application problem occurs when designers try to connect high-impedance sources to the reference pins of in amps. This often introduces serious errors, especially in in-amp circuits which are comprised of three op amps, and their monolithic IC equivalents. **Figure 8** makes this problem easier to understand.

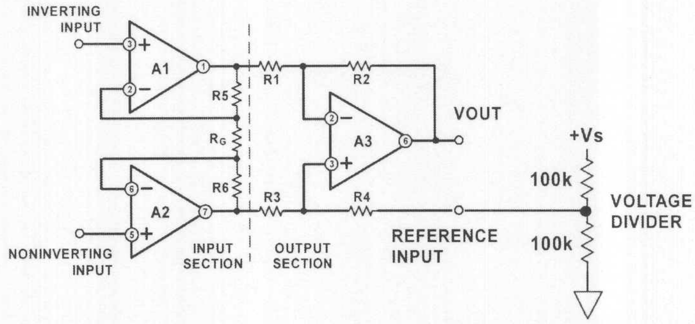

Figure 8. Incorrect use of a simple voltage divider to directly drive the reference pin of an in amp (Click on figure to enlarge)

This example uses the standard three op-amp in-amp circuit; most IC in-amps also follow this same basic architecture. The in amp has its reference pin tied directly to a simple voltage divider. The voltage divider ties directly to resistor R_4 in the in-amp's subtractor section; therefore, it becomes part of the R_3/R_4 subtractor network. Note that any added resistance between R_4 and ground increases the total resistance of R4 and unbalances the subtractor section.

This, in turn, reduces both the in-amp's common-mode rejection and its gain accuracy. Attempts to use small resistor values in the voltage divider will increase power-supply current consumption, may overheat the resistors, and certainly is not a good design approach.

Figure 9 shows a much better solution: here an op-amp buffer amplifier is inserted between the voltage divider and the in-amp's reference pin.

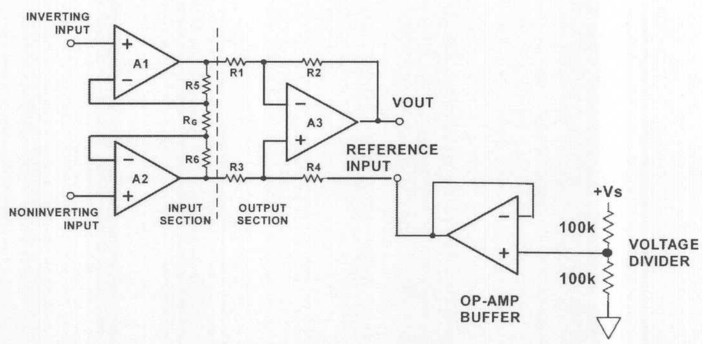

Figure 9: Driving the reference pin of an in amp from the low-impedance output of an op amp (Click on figure to enlarge)

However, note that even though the reference is now being driven by a very low-impedance source (typically less than one ohm), the addition of the op-amp buffer alone still leaves a potential problem: lack of adequate power-supply rejection.

4) Preserving PSRR when amplifiers are referenced from the supply line using voltage dividers.
Often overlooked is the very important issue of power-supply rejection (PSR) both with in-amp and op-amp circuits. Power supply rejection isolates an amplifier from power-supply hum, noise, and any voltage variations present on the power-supply line. This is important because many real-world circuits are powered by less than ideal supplies. Also, any AC signals present on the supply lines can be fed back into the circuit, amplified and, if conditions are right, cause a parasitic oscillation.

Modern op amps and in amps all provide substantial power-supply rejection as part of their design. This

is something that most engineers take for granted. Many modern op amps and in amps have power-supply rejection ratio (PSRR) specifications of 80 dB to over 100 dB, reducing power-supply variations on the amplifier by a factor of 10,000 to 100,000. Even a fairly modest value of 40 dB PSRR isolates the supply from the amplifier by a factor of 100.

However, when designers use a simple resistor divider and op-amp buffer to supply a reference voltage for an in amp, any variations in power-supply voltage travel through this circuitry and directly vary the in-amp's output level. Therefore, unless low-pass filtering is provided, the normally excellent PSRR of the IC is lost.

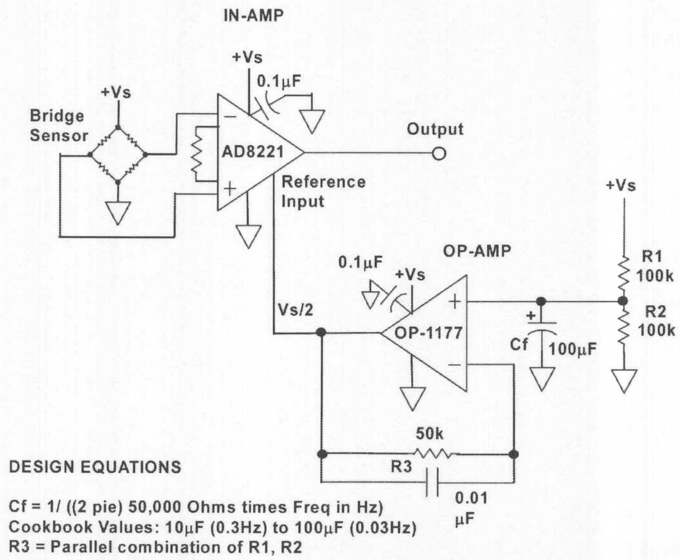

Figure 10: Decoupling the reference circuit to preserve the in-amp PSRR
(Click on figure to enlarge)

In **Figure 10**, a large capacitor has been added to the voltage-divider network to decouple it from power-supply variations and preserve PSRR.

Here the -3 dB pole of this filter is set by the parallel combination of R_1/R_2 and the decoupling capacitor C_1. The pole should be set approximately ten-times lower than the low-frequency bandwidth of the circuit. The -3 dB pole frequency is equal to $1/(2\pi RC_1)$, where $R= (R_1 \bullet R_2)/2)$.

A good "cookbook" rule of thumb is to use two 100 kΩ resistors for R_1 and R_2, and to make C_1 100 μF or more. This provides a -3 dB pole frequency of approximately 0.03 Hz. Note that the second small capacitor across the 50 kΩ op-amp feedback resistor simply cancels-out any resistor noise.

Designers should also keep in mind that the R_1/R_2, C_1 network will take time to charge up. Using our cookbook values, that turn-on time T is equal to RC, where R equals 50 kΩs (the parallel combination of R_1, R_2) and C_1 equals 100 μF. In this case, the voltage applied to the in-amp's reference pin will be delayed by five seconds.

The circuit of **Figure 11** offers a further refinement.

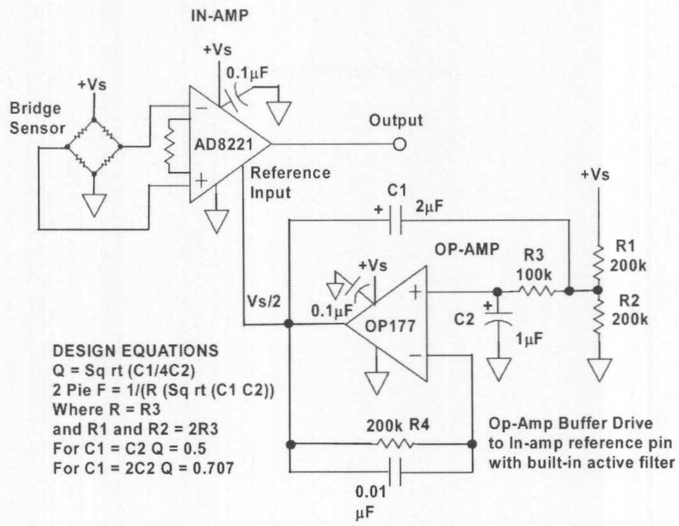

Figure 11: An op-amp buffer, operating as an active filter, drives the reference pin of an in-amp (Click on figure to enlarge)

Here, the op-amp buffer is operated as an active filter, which allows the use of much-smaller capacitors for the same amount of power-supply decoupling. In addition, the active filter can be designed to provide a higher Q and thus give a quicker turn-on time.

Test results: With the component values shown, and +12 V applied, a +6 V filtered reference voltage was provided to the in amp. A 1 V_{p-p} sinewave of varying frequency was used to modulate the +12 V supply, with the in-amp gain set to one.

Under these conditions, no AC signal was visible on an oscilloscope, at V_{ref} or at the in-amp output, until approximately 8 Hz. Measured supply range for this circuit was +4 V to greater than +25 V, with a low-level input signal applied to the in amp. Circuit turn-on time was approximately two seconds.

5) Decoupling single-supply op-amp circuits
Single-supply op-amp circuits are often referenced from the power-supply line using voltage dividers. Therefore, they also require adequate decoupling to preserve PSRR.

In single-supply circuits, a very common and incorrect practice is to use a 100 kΩ/100 kΩ resistor divider with a 0.1 μF bypass capacitor, to supply $V_s/2$ to the inverting pin of the op amp. Using these values, power-supply decoupling is often inadequate, as the pole frequency is only 300 Hz. Circuit instability ("motor boating") often occurs, especially when driving inductive loads.

Figure 12 and **Figure 13** show examples for inverting and non-inverting single-supply op-amp circuits.

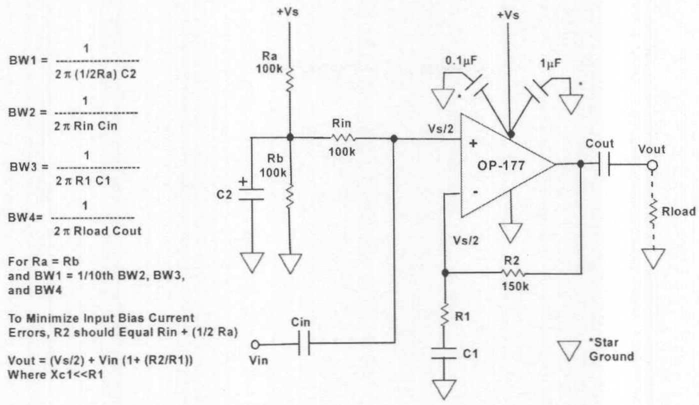

Figure 12: A single-supply non-inverting amplifier circuit showing correct power-supply decoupling

(Click on figure to enlarge)

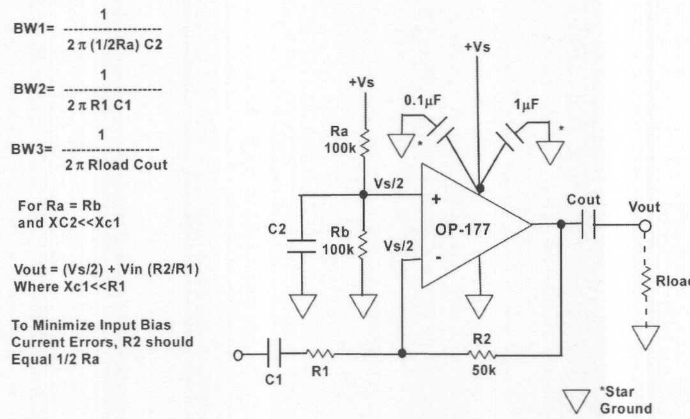

Figure 13: Proper decoupling for a single-supply inverting amplifier circuit

(Click on figure to enlarge)

A good rule of thumb when using a 100 kΩ/100 kΩ voltage divider, as shown, is to use a C_2 value of at least 10 μF for a 0.3 Hz, -3 dB rolloff. A value of 100 μF (0.03 Hz pole) should be sufficient for nearly all circuits.

Related articles of interest
1. *Basics of using precision instrumentation amplifiers in single-supply designs,* Bjoy Santos, Intersil Corporation, click here
2. *Five basic mistakes to avoid when using instrumentation amplifiers,* Matthew Duff, Analog Devices, Inc., click here

About the author
Charles Kitchin is an applications engineer at Analog Device, Inc. (Wilmington, MA). His responsibilities include writing technical publications and developing applications circuits. He has published more than 80 technical articles and design ideas, three books, and numerous application notes.